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(54) **METHOD FOR FORMING A MAGNETIC SENSOR THAT USES A LORENTZ FORCE AND A PIEZOELECTRIC EFFECT**

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Related U.S. Application Data

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(51) **Int. Cl.**[7] **G01R 33/02**

(52) **U.S. Cl.** **324/244**; 324/260; 427/457; 427/458

(58) **Field of Search** .... 118/723 MA; 427/457, 427/458, 547; 324/244, 260

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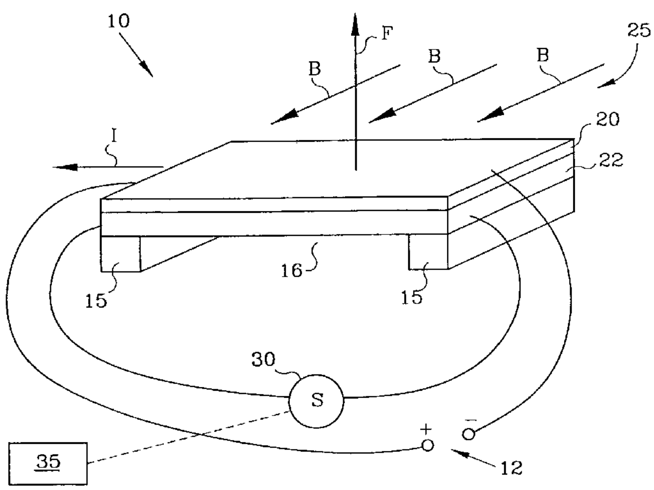
(57) **ABSTRACT**

A method and apparatus for sensing a presence of a magnetic field and/or a magnitude of a magnetic flux density of the magnetic field. A direct-current voltage is applied across a first layer of a conductive material, so that a direct current flows in a first direction through the first layer. A second layer of a piezoelectric material is integrated with or positioned adjacent or abutting the first layer. The first layer and the second layer are exposed to or positioned within a magnetic field. A Lorentz force is thus caused, preferably in a direction which is generally perpendicular to the first direction of the direct current and a second direction of the magnetic field to deflect the piezoelectric material thereby causing an output voltage in response to the Lorentz force. A magnetic flux density can be calculated as a function of the piezoelectric output.

31 Claims, 1 Drawing Sheet



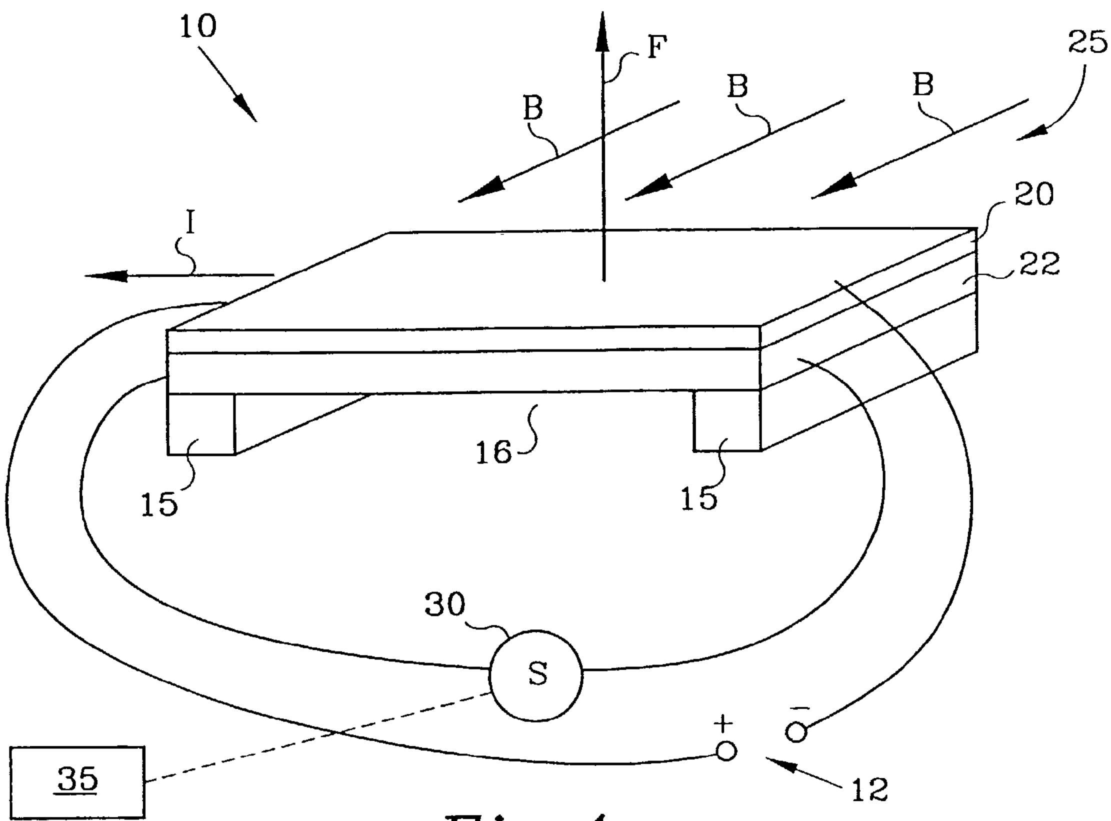


Fig. 1

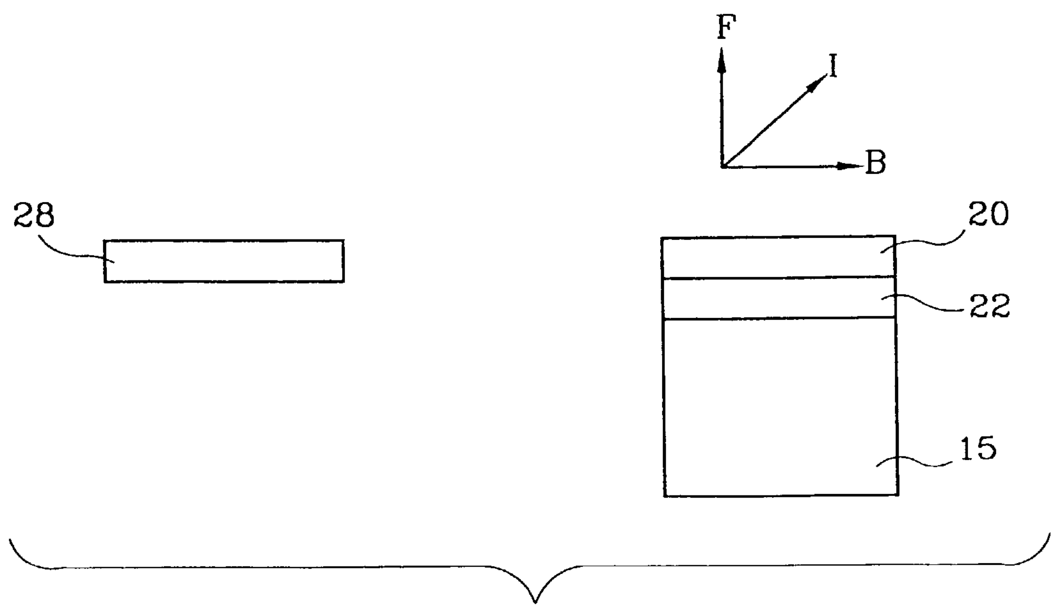


Fig. 2

METHOD FOR FORMING A MAGNETIC SENSOR THAT USES A LORENTZ FORCE AND A PIEZOELECTRIC EFFECT

This application is a divisional application of application Ser. No. 09/653,835, filed on Sep. 1, 2000 now U.S. Pat. No. 6,426,621.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a method and an apparatus for sensing a magnetic field and for detecting a magnetic flux density, each as a function of a measured Lorentz force.

2. Discussion of Related Art

Hall sensors have been used to sense magnetic fields. Hall effect transducers have been used with pole pieces and biasing magnets to increase sensitivity of the Hall sensors. When used with a magnet, a pole piece tends to channel a magnetic field and thus change flux densities in a magnetic circuit.

U.S. Pat. No. 4,992,659 discloses a microscopy apparatus for measuring Lorentz force-induced deflection of a tip of a scanning tunneling microscope to image magnetic structures of a sample. Motion of the tip, which indicates the presence of a magnetic field, is optically detected. The magnetic field measurement and a tip position are received by a computer which provides an output signal to a device for graphically representing the magnetic field at different positions on a surface of the sample.

U.S. Pat. No. 5,675,252 discloses a piezomagnetometer which uses a magnetoelectric composite structure, formed by alternating layers of piezoelectric and magnetostrictive material, to convert a fluctuating magnetic field directly to electric current. An ambient magnetic field strains magnetostrictive layers which stresses piezoelectric layers and drives a polarization current proportional to an amplitude of the magnetic field.

It is apparent that there is a need for a method and apparatus that enables a microelectronic structure to sense a magnetic field and to measure a magnetic flux density. There is also a need for a method and apparatus that produces a significantly higher output voltage, as compared to conventional methods and apparatuses, when exposed to the same magnetic field.

SUMMARY OF THE INVENTION

It is one object of this invention to provide a method and apparatus that uses a Lorentz force and a piezoelectric effect to detect the presence of a magnetic field and to measure a magnetic flux density of the magnetic field.

It is another object of this invention to provide a microelectronic structure that detects the presence of a magnetic field and measures a magnetic flux density of the magnetic field.

It is still another object of this invention to provide a method and apparatus that produces a significantly higher output voltage signal, as compared to known methods and apparatuses, when exposed to the same magnetic field.

The above and other objects of this invention are accomplished with a method for sensing a magnetic field wherein a direct-current voltage is applied across a first layer of a conductive material. A direct current flows in a first direction through the first layer. A second layer of piezoelectric material is either integrated with or is adhered to the first layer. The first layer and the second layer are positioned within or exposed to the magnetic field. A Lorentz force generated in a second direction, which is preferably but not necessarily generally perpendicular to the first direction, is generated causing the piezoelectric material to deflect. The presence of a magnetic field and/or a magnetic flux density of the magnetic field can be calculated as a function of the measured Lorentz force.

In one preferred embodiment according to this invention, the direct current is in a range of about 0.1 mA to about 10 mA, and preferably about 3 mA. Also in a preferred embodiment of this invention, a magnitude of the magnetic flux density is in a range of about 100 Gauss to about 1,000 Gauss, preferably about 400 Gauss.

The first layer of the conductive material and the second layer of the piezoelectric material can be moved within the magnetic field into a position where the magnitude of the Lorentz force is at a maximum value. In such position where the Lorentz force is at a maximum value, the two vectors representing the direct current and the magnetic field are at a right angle with respect to each other. The Lorentz force is generated in a direction which is preferably generally perpendicular to the directions of the vectors of the direct current and the magnetic field.

In one preferred embodiment according to this invention, an apparatus for sensing a magnetic field comprises the first layer of the conductive material integrated with, or applied to, the second layer of the piezoelectric material, such as by a sputtering technique or other suitable deposition technique. As the layer of piezoelectric material changes shape it produces a change in voltage. A sensor can then measure the Lorentz force generated by measuring the voltage. A computer is preferably used to receive the transducer output signal corresponding to the measured Lorentz force. The computer then calculates either the presence of a magnetic field or a magnitude of the magnetic flux density, as a function of the measured Lorentz force, using any suitable analog and/or digital circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

The above-mentioned and other features and objects of this invention will be better understood from the following detailed description when taken in view of the drawings wherein:

FIG. **1** is a perspective schematic diagram of an apparatus according to one preferred embodiment of this invention; and

FIG. **2** is a schematic end view of a pole piece positioned near an apparatus, according to one preferred embodiment of this invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

Apparatus **10**, which is used to sense a presence of magnetic field **25** and/or to measure a magnetic flux density of magnetic field **25**, comprises base **15**, first layer **20** and second layer **22**. The elements are preferably sized, shaped and otherwise designed so that apparatus **10** forms a microelectronic structure. Apparatus **10** and the corresponding method of this invention uses a combination of Lorentz force and piezoelectric effect to determine the presence of magnetic field **25** and/or to measure the magnetic flux density of magnetic field **25**. In one preferred embodiment the magnetic flux density is in a selected range of about 100 Gauss to about 1000 Gauss. The physical size, layout and/or materials of the different elements of apparatus **10** can be modified according to the strength of magnetic field **25** and/or the desired output voltage from apparatus **10**.

As shown in FIG. **1**, second layer **22** spans two support surfaces of base **15**, forming gap **16**. Second layer **22** is preferably attached to, secured to or otherwise fixed to base **15** so that second layer **22** can deflect in a controlled or consistent fashion. Second layer **22** is constructed of a piezoelectric material, such as polyvinylidene fluoride, a copolymer of a polyvinylidene fluoride, or another suitable material that exhibits a change in voltage or electromotive force as a function of a change in shape. Piezoelectric materials suitable for use with this invention are known to those skilled in the art of microelectronic structures.

As shown in FIG. **1**, second layer **22** spans or forms a bridge across the support surfaces of base **15**. However, second layer **22** and base **15** can form any other suitable structure that accommodates or allows second layer **22** to deflect or change shape, such as when exposed to or introduced within magnetic field **25**. Second layer **22** preferably but not necessarily has an overall strip shape, for example having a length in a range of about 1 mm to about 5 mm, a width in a range of about 0.05 mm to about 0.15 mm and a thickness in a range of about 0.001 mm to about 0.010 mm. Base **15** can have any suitable shape or structure that provides support for second layer **22** and that allows at least a portion of second layer **22** to deflect or otherwise change shape. For example, rather than a spanning beam, second layer **22** may form a cantilever structure having only one end fixed to base **15**, wherein second layer **22** extends over gap **16**. Base **15** preferably forms gap **16** over which second layer **22** spans.

Base **15** is preferably constructed of a dielectric material, such as silicon, a composite containing silicon, or any other suitable material that has non-conductive properties, as known to those skilled in the art of microelectronic structures. Base **15** can be etched or produced with any other suitable manufacturing processes, also as known to those skilled in the art of microelectronic structures.

First layer **20** is preferably constructed of a conductive material, such as copper, gold and/or aluminum. In one preferred embodiment according to this invention, first layer **20** is applied to second layer **22** using an electrical depositing method, such as a suitable sputtering technique as known to those skilled in the art of microelectronic structures. First layer **20** is positioned adjacent or abuts second layer **22** and thus preferably has similar dimensions to second layer **22**.

Voltage source **12** is attached to or across first layer **20** so that a direct current passes through first layer **20**, in a first direction. In one preferred embodiment according to this invention, the direct current is in a range of about 0.1 mA to about 100 mA, preferably about 3 mA. Voltage source **12** may comprise a battery or any other suitable direct-current voltage source known to those skilled in the art.

As shown in FIG. **1**, sensor **30** is attached to or connected to second layer **22** so that sensor **30** measures a voltage output from the piezoelectric second layer **22** corresponding to Lorentz force F generated in a second direction. In one preferred embodiment of this invention, the second direction of the Lorentz force is generally perpendicular to the first direction of the direct current passing through first layer **20**. Sensor **30** may also comprise an output for emitting an output signal which is proportional to a magnitude of the Lorentz force. It will be appreciated that Lorentz force F is maximal when the current and the magnetic field are perpendicular.

Apparatus **10** may also comprise computer means **35** for receiving the output signal and for calculating a presence of magnetic field **25** and/or a magnitude of and/or a direction of the magnetic flux density of magnetic field **25**, preferably as a function of the measured Lorentz force. Computer means **35** may comprise any suitable hardware and/or software suitable for storing data and performing mathematic functions and/or algorithms. For example, an open-circuit output voltage (V) of second layer **22** can be calculated according to the following known equation:

$$V=g_{31}\,(F/wt)\,(t)=g_{31}\,(F/W)$$

where F is the magnitude of the Lorentz force, w is the width of second layer **22**, t is the thickness of second layer **22**, and g_{31} is the piezoelectric coefficient mode of second layer **22**. According to the above equation, with second layer **22** shaped as a beam with w=0.1 mm, the length (L)=3 mm, and with second layer **22** attached to base **15** at two locations and spanning gap **16**, when exposed to magnetic field **25** having a magnetic flux density of 400 Gauss, the measured Lorentz force F is about 36×10^{-6} Newton with a 0.8 mV piezoelectric output.

In one preferred embodiment according to this invention, the Lorentz force changes, such as by stretching, the shape of second layer **22**. Because second layer **22** behaves as a strain gauge, a signal, such as the 0.8 mV signal, is generated. The 0.8 mV signal is much greater than signals generated from other conventional strain gauges that require further amplification to reach a magnitude similar to the magnitude achieved with apparatus **10** of this invention. For example, a conventional Hall sensor having a similar shape and dimensions would produce an output voltage of about 1.5×10^{-6} mV when positioned within a magnetic field having the same magnetic flux density of 400 Gauss.

The Lorentz force F is also expressed according to the following equation:

$$F=(I\times B)L$$

where I is the direct current vector and B is the magnetic field vector. The Lorentz force F reaches a maximum value when the two vectors I and B are positioned at right angles with respect to each other. Thus in one preferred embodiment of this invention, apparatus **10** is positioned within magnetic field **25** so that the Lorentz force F is in the second direction which is generally perpendicular to the first direction of the direct current vector I and to the third direction of the magnetic field vector B.

Referring to FIG. **2**, in another preferred embodiment according to this invention, apparatus **10** further comprises pole piece **28** or a bias magnet. Pole piece **28** is used to alter magnetic field **25** of this invention in a fashion similar to how pole pieces are used in combination with conventional Hall sensors.

In one preferred embodiment of a method according to this invention, the direct-current voltage is applied across or to first layer **20** so that the direct current flows or passes through first layer **20**, in the first direction. The direct-current voltage and/or the direct current can be measured and varied using meters, circuits and/or voltage devices which are known to persons skilled in the art of microelectronic sensors.

Second layer **22** is adhered and positioned adjacent, or abuts, or is integrated with first layer **20**. First layer **20** and second layer **22** are positioned within or exposed to magnetic field **25**. In one preferred embodiment, apparatus **10** can be moved or positioned to generate the maximal Lorentz force F by placing the first direction of the direct current perpendicular to the third direction of magnetic field **25**. it will be appreciated that F is always perpendicular to the current direction and the magnetic field, and that the strength of F decreases as the perpendicular vector of current to magnetic field decreases.

The generated Lorentz force F deflects second layer **22** which outputs a voltage which is measured as an output signal and is preferably transmitted to computer means **35**. The measured Lorentz force F can then be used to detect the presence of magnetic field **25** and/or to measure the magnitude of the magnetic flux density of magnetic field **25**.

While in the foregoing specification this invention has been described in relation to certain preferred embodiments thereof, and many details have been set forth for purpose of illustration it will be apparent to those skilled in the art that the invention is susceptible to additional embodiments and that certain of the details described herein can be varied considerably without departing from the basic principles of the invention.

I claim:

1. A method for sensing a magnetic field, comprising:

(a) providing a substrate;

(b) etching the substrate to provide a gap;

(c) forming a conductive layer extending at least partially over the gap;

(d) forming a piezoelectric layer extending over the gap and positioned adjacent to the conductive layer;

(e) applying a direct-current voltage across the conductive layer wherein a direct current flows in a first direction;

(f) positioning the piezoelectric layer within a magnetic field and generating a Lorentz force in a second direction generally perpendicular to the first direction to deflect the piezoelectric layer;

(g) emitting a signal output from the piezoelectric layer as a function of a generated Lorentz force; and

(h) calculating a magnetic flux density of the magnetic field as a function of the voltage output of the piezoelectric layer as caused by the Lorentz force.

2. The method of claim **1** further comprising the step of forming the conductive layer and the piezoelectric layer by applying an electrical deposition technique.

3. The method of claim **2**, wherein the electrical deposition technique is a sputtering technique.

4. The method of claim **1** further comprising the steps of forming the conductive layer as a first strip and forming the piezoelectric layer as a second strip that are substantially similar in size and shape.

5. The method of claim **1** further comprising the step of adhering the piezoelectric layer to the conductive layer.

6. The method of claim **1** further comprising the step of integrating the piezoelectric layer with the conductive layer.

7. The method of claim **1** further comprising the step of forming the piezoelectric layer of a material that can change shape to emit the output signal.

8. The method of claim **1**, wherein the step of forming the piezoelectric layer comprises the step of forming the piezoelectric layer such that it can change shape when exposed to the Lorentz force.

9. The method of claim **1**, wherein the piezoelectric layer is a polyvinylidene fluoride.

10. The method of claim **1**, wherein the piezoelectric layer is a copolymer of a polyvinylidene fluoride.

11. The method of claim **1**, wherein the step of etching the substrate comprises the step of etching the substrate to form at least two support surfaces to form the gap and wherein the step of forming the piezoelectric layer comprises the step of forming the piezoelectric layer as a bridge across the gap formed by the at least two support surfaces.

12. The method of claim **1**, wherein the step of etching the substrate comprises the step of etching the substrate to form at least two support surfaces to form the gap and wherein the step of forming the piezoelectric layer comprises the step of forming the piezoelectric layer as a cantilever structure with at least one end of the piezoelectric layer attached to at least one of the at least two support surfaces.

13. The method of claim **1** further comprising the step of providing a pole piece in communication with the first layer and the second layer.

14. The method of claim **1**, further comprising the step of providing the signal to a computer and calculating a magnitude of a magnetic flux density as a function of the Lorentz force.

15. The method of claim **14**, further comprising the step of providing the signal to a computer and calculating whether the magnetic field is present.

16. A method for forming a magnetic sensor, comprising the steps of:

providing a substrate;

etching the substrate to provide at least one support surface;

forming a second layer spanning at least a portion of the substrate having the at least one support surface such that at least a portion of the second layer is deflectable; and forming a first layer adjacent the second layer;

applying a direct-current voltage across the first layer wherein a direct current flows in a first direction:

positioning the second layer within a magnetic field and generating a Lorentz force in a second direction generally perpendicular to the first direction to deflect the second layer;

emitting a signal output from the second layer as a function of a generated Lorentz force; and

calculating a magnetic flux density of the magnetic field as a function of the voltage output of the second layer as caused by the Lorentz force.

17. The method of claim **16**, wherein the first layer is a conductive layer.

18. The method of claim **17** further comprising the step of providing a voltage source to the conductive layer.

19. The method of claim **16**, wherein the second layer is a piezoelectric layer.

20. The method of claim **19**, wherein the step of forming the piezoelectric layer comprises the step of forming the piezoelectric layer such that it can change shape when exposed to the Lorentz force.

21. The method of claim **19** further comprising the step of adhering the piezoelectric layer to the conductive layer.

22. The method of claim **19** further comprising the step of integrating the piezoelectric layer with the conductive layer.

23. The method of claim **19**, wherein the piezoelectric layer is a material that can change shape to produce a change in voltage.

24. The method of claim **16**, wherein the step of providing for an output comprises the step of providing the output to a computer and calculating a magnitude of the magnetic flux density as a function of the Lorentz force.

25. The method of claim **16**, wherein the step of providing for an output comprises the step of providing the output to a computer and calculating whether the magnetic field is present.

26. The method of claim **16**, wherein the substrate is a material that is non-conductive.

27. The method of claim **16**, wherein the substrate is a dielectric material.

28. The method of claim **16** further comprising the step of providing a sensor in communication with the second layer to measure the output.

29. The method of claim **16** further comprising the step of providing a pole piece in communication with the first layer and the second layer.

30. The method of claim **16**, wherein the step of etching the substrate comprises the step of etching the substrate to form at least two support surfaces and wherein the step of forming the second layer comprises the step of forming the second layer as a bridge across the at least two support surfaces.

31. The method of claim **16**, wherein the step of etching the substrate comprises the step of etching the substrate to form at least two support surfaces and wherein the step of forming the second layer comprises the step of forming the second layer as a cantilever structure with at least one end of the second layer attached to at least one of the at least two support surfaces.

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